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PHYSICAL MODELING TECHNIQUES FOR MISSILE AND OTHER PROTECTIVE STRUCTURES

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The following technical papers have been reviewed by our office and are approved for public release. This headquarters has no objection to their public release and authorizes publication.

1. (BMO 81-296) "Protective Vertical Shelters" by Ian Narain, A.M. ASCE, Jerry Stepheno, A.M. ASCE, and Gary Landon, A.M. ASCE.

2. (BMO 82-020) "Dynamic Cylinder Test Program" by Jerry Stephens, A.M. ASCE.

3. (AFCMD/82-018) "Blast and Shock Field Test Management" by Michael Noble.

4. (AFCMD/82-014) "A Comparison of Nuclear Simulation Techniques on Generic MX Structures" by John Betz.

5. (AFCMD/82-013) "Finite Element Dynamic Analysis of the DCT-2 Models" by Barry Bingham.

6. (AFCMD/82-017) "MX Basing Development Derived From H. E. Testing" by Donald Cole.

7. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Experimental Program" by J. I. Daniel and D. M. Schultz.

8. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Specimen Construction" by A. T. Ciolko.

9. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Instrumentation and Load Control" by N. W. Hanson and J. T. Julien.

10. (BMO 82-003) "Laboratory Investigation of Expansion, Venting, and Shock Attenuation in the MX Trench" by J. K. Gran, J. R. Bruce, and J. D. Colton.

11. (BMO 82-003) "Small-Scale Tests of MX Vertical Shelter Structures" by J. K. Gran, J. R. Bruce, and J. D. Colton.

12. (BMO 82-001) "Determination of Soil Properties Through Ground Motion Analysis" by John Frye and Norman Lipner.

13. (BMO 82-062) "Instrumentation for Protective Structures Testing" by Joe Quintana.

14. (BMO 82-105) "1/5 Size VHS Series Blast and Shock Simulations" by Michael Noble.

15. (BMO 82-126) "The Use of Physical Models in Development of the MX Protective Shelter" by Eugene Sevin.

*16. REJECTED: (BMO 82-029) "Survey of Experimental Work on the Dynamic Behavior of Concrete Structures in the USSR" by Leonid Millstein and Gajanen Sabnis.

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27 APR 1982

THE USE OF PHYSICAL MODELS IN DEVELOPMENT OF THE M-X PROTECTIVE SHELTER

By Eugene Sevin[1]

1. INTRODUCTION

At the heart of the controversy over the M-X weapons system development has been the plan for basing the missile; that is, how a force of some 200 M-X missiles can be made to survive a massive attack of several thousand nuclear weapons. Until recently, the preferred basing was the so-called Multiple Protective Structure (MPS) concept where the actual locations of the missiles were concealed among a large number of hardened structures under the assumption that an enemy could not "afford" to attack all possible locations.

In view of the presumed accuracy of enemy warheads, no one shelter is intended to survive a direct nuclear attack. However, to enforce the "price," multiple shelter kills from the same attacking weapon must be avoided. Thus, the requirement for nuclear hardening (i.e., to avoid collateral damage from an attack on a neighboring shelter) has been a primary consideration in shelter configuration, land requirements (i.e., shelter spacing) and, hence, system cost.

While the level of hardening selected for the several MPS variants generally has been well within the state-of-the-art of protective facility design, the magnitude of the construction program ($3 billion for shelter-related costs in FY 1978 dollars; $11 billion for the entire military construction program--about twice as much in "then year" dollars) is nearly without precedent. Thus, cost considerations have motivated the search for innovative structural concepts and construction methods, and have driven design margins to the minimum. It has been in the latter regard that physical modeling has played an extremely influential role in the M-X shelter design process.

The majority of the papers in this section deal with one or another aspect of these activities undertaken in support of M-X protective shelter development over the past six years. This paper considers the scope of physical modeling employed in the design of the three primary protective shelter concepts for the M-X missile: the Shallow Buried Trench, the Vertical Shelter (Silo), and the Horizontal Shelter. However, emphasis is on the trench-related models because they are more innovative and relatively less well known.

2. OVERVIEW

In 1976, the Air Force entered into a two-year concept validation program to select a final (sic!) basing mode for the M-X missile. The

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two main candidates at that time were the (1) Horizontal Shelter--an earth-mounded, garage-type structure for a single missile and its transporter/erector/launcher (TEL) interconnected by an extensive open road network, and (2) the Shallow Buried Trench--a single 35 km long section of underground tube allowing random movement of a missile/TEL "train." The entire 200 M-X missile force would require either 4600 horizontal shelters or 200 lengths of buried trench to meet minimal survival goals under the postulated threat.

As the horizontal shelter and buried trench designs became better defined, and their estimated costs increased, interest was renewed in other basing alternatives. A comprehensive basing review was undertaken in mid-1978 and, as a result, both concepts were abandoned in favor of a vertical shelter system. As seems to be the fate of M-X, however, the silo was replaced only one year later by a more austere version of the horizontal shelter, as a consequence of mounting concerns over arms control implications--a principal reason for rejecting silos in the first place. Thus, by 1980, M-X basing virtually had come full-circle.

The nuclear hardness requirement for both the horizontal shelter and buried trench concepts was selected to be in the 400 to 600 psi overpressure range on the basis of system cost optimization studies. (N.B. 600 psi peak surface pressure occurs at a distance of about 565 m from a one megaton (1 MT) surface burst). Optimum hardness for the vertical shelter was determined to be between 1000 and 1500 psi.

Each shelter concept was to be hardened in a balanced manner against all nuclear weapons effects (e.g., nuclear and thermal radiation, electromagnetic pulse, dynamic pressures, and crater ejecta), and physical models were employed extensively to develop design approaches and to gather hardness data in all of the disciplines involved. This paper, however, will be concerned entirely with the use of physical models relating to blast and shock resistant design.

The scope of the modeling effort undertaken for the three basic shelter configurations is summarized in the Test Objective Matrix tables (Tables 1-3). These activities were conducted over a six-year period and involved major laboratory and field investigations employing mechanical test devices, high explosive (HE) simulations of nuclear airblast and ground shock, and underground nuclear tests.

Small-scale (1/100 to 1/40) non-responding models were used to determine airblast loads on the horizontal shelter. Intermediate scale (1/21 to 1/5) responding models of generic structural elements provided information on critical response features for all concepts, assisted in the screening of alternative shelter design approaches, and lent insight into fidelity requirements for blast and shock load simulators. Larger scale (1/2 to 3/4) models of complete structural systems, notably for the buried trench and horizontal shelter concepts, helped resolve significant design issues relating to structure-medium interaction, structural subsystem interactions, and the motion environment specifications fo internal shelter equipment. Relatively lesser effort was devoted to the vertical shelter because of the existing data base for silo structures.

3. THE SHALLOW BURIED TRENCH

In the shallow buried trench concept, location of the missile was concealed by its intermittent movement within a buried tube. The original baseline design, uniformly hardened against 600 psi peak surface loads (Fig. 1), was a fiber-reinforced concrete cylinder, 4 m internal diameter, 40 cm thick with 1.5 m soil overburden. The missile canister could be erected at any location by being forced up through the roof of the tube and soil overburden; the top was jointed to facilitate this action. (N.B. Two alternative full-sized breakout mechanisms were demonstrated successfully during trench development.) In view of its large cost, a hybrid trench concept subsequently was developed with hardened sections every several thousand feet (from which the missile could be erected more conveniently) connected by unhardened tube sections of conventional design.

To protect the missile against the possibility of airblast entering through damaged "upstream" portions of the trench, massive plugs were provided at either end of the missile/TEL train. The uniformly hardened tube had internal ribs that acted as stiffeners and aided in locking the blast plugs to the tube walls. Eliminating the ribs in the hybrid design was another significant cost saving.

A variety of physical models were used to gain insight into the loading and response of the tube structure and blast plugs in an effort to demonstrate the feasibility of the concept and to develop a data base for minimum cost design. The scope of this ambitious experimental program is summarized in the Test Objective Matrix, Table 1. The purpose of most of the structural model testing was to determine response modes and post-yield capacity of the fiber-reinforced concrete tube for a representative range of cylinder and backfill stiffness and breakout joint details. The principal static response tests /1-3/ and dynamic response tests /4, 5/ are reported in this session.

The blast plug was a major design consideration. It was postulated that airblast loads could be introduced into the tube upstream of the blast plugs by (1) airblast leakage through tube sections damaged by surface pressures in excess of 600 psi, (2) internally generated airblast due to piston-like implosion of the tube (caused by external airblast and ground shock loading) or, for small miss distances, (3) breeching of the tube by the attacking weapon or the resulting crater.

Inasmuch as the latter case could not be ruled out from projections of weapon delivery accuracy, the concern that the trench might become a gigantic nuclear shock tube destroying everything within, came to be the dominant feasibility issue for the trench concept. Theoretical studies indicated that pressure leakage within the tube would not produce as severe in-tube environments as the other mechanisms. Two possible implosion modes were considered, one dominated by the close-in ground shock and the other, a progressive collapse of the tube roof, caused by the surface airblast. The latter so-called "toothpaste tube" response was investigated early-on in a high explosive field experiment in which a 1/8 scale section of tube was exposed to peak surface overpressures decaying from 5000 psi to 1500 psi along its length /6/. The test results demonstrated that progressive collapse of the tube could occur, but would not give rise to a propagating air shock, despite measured local pressure peaks of nearly a kilobar. This served to corroborate theoretical analyses and led to dismissing this mechanism as a means of generating significant in-tube pressures.

Preliminary calculations suggested that the ground shock-induced implosion mechanism depended sensitively on the nature of the coupling and tube collapse mechanism, and could cause a much more severe in-tube environment. This mode of response was studied experimentally in a series of high explosive tests on a 1/16 scale section of buried tube /7/. The experimental setup is shown in Fig. 2. A rectangular slab of TNT was positioned on the ground surface directly above the tube and sized to induce a 90 kbar shock at the tube wall (based on source region predictions). Primary instrumentation consisted of high-speed photography to record the tube collapse process, air and impact pressures within the rapid closure region directly under the charge, shock time of arrival (TOA), pressures along the tube and conditions within the free-field.

Two instrumentation check-out tests were conducted using commercially available 6 in diameter concrete pipe. Fig. 3 shows the collapse process at a cross-section within the rapid closure region as constructed from high-speed photographic records obtained in one of these tests. A comparison with pre-test predictions also is shown. While the general shape and timing of the upper tube surface is reproduced well, formation of the two-lobe pattern was not anticipated. It was estimated that the pressure within the lobes did not exceed about 1 kbar, and was the first indication that this collapse mechanism might not prove effective in generating a strong shock in the tube.

Data recovery from the main experiment was disappointing. The Fastax camera broke before reaching full speed, and only the first phase of tube collapse within the rapid closure region was recorded. Even then, surface blow off material obscured much of the early time record. Nevertheless, observations were consistent with those of the preliminary tests. The lobe pattern formed, trapping air at the sides of the tube and preventing the uniform build-up of large pressures as the tube completely collapsed. Pressures along the tube, as measured and inferred from TOA data, are shown in Fig. 4, indicating the absence of a strong propagating air shock outside of the rapid closure region. The results of these experiments led to the development of a "leaky-piston" response model for the ground shock-dominated collapse mechanism, according to which the preliminary estimates of the in-tube environment were reduced significantly.

The breeching mechanism refers to the direct coupling of a portion of the bomb's energy to the tube and occurs whenever the radius of vaporization (about 10 m for a 1 MT burst) intersects a portion of the tube. A worst case scenario clearly is when the bomb lands directly overhead, penetrates the overburden, and detonates inside the tube. In this event, initially all of the bomb's energy is coupled directly to the tube.

A more probable occurrence is when the bomb detonates on the surface directly overhead. It is estimated that only about 1 percent of the energy couples to the tube in this case, the balance going into the fireball (95%) and other regions of the ground. Unfortunately, reducing a 1 MT on-line surface burst to the equivalent of a 10 KT in-tube burst did not appear to resolve the feasibility of designing a survivable blast plug.

Detailed two-dimensional radiation coupled hydrodynamic calculations indicated that (for a 1 MT surface burst) only about 30 percent of energy initially coupled remains in the (volume bounded by the expanding) tube after the first 100 msec /8/. The effective source region for the in-tube airblast consists of hot vaporized soil and tube wall material mixed with air extending out to about 6 m in either direction from the point of the explosion. At these early times, the shock pressures in the tube remain relatively constant as the mitigating effects of various flow loss mechanisms are counteracted by the collapsing action of the tube under the outrunning surface air blast. The interior shock was expected to overtake the surface airblast after about 7 msec (and 180 m from the source), whereupon expansion of the tube volume and venting of tube gases to the atmosphere became significant loss mechanisms.

The gas behind the shock front at this time is in a very high enthalpy state (pressures of 5-15 kbar and temperatures of 1-10 electron volts), far in excess of the level required to vaporize the tube walls. While entrainment of ablated wall material serves to slow and cool the flow, the quantitative effect depends strongly on the formation of a turbulent boundary layer behind the shock and the consequent flow mixing process. At pressures below about 10 kbar, the shock attenuating effect of wall friction was thought to be important also.

An intensive effort was undertaken to model these loss mechanisms and to quantify their influence on shock attenuation. The "then" state-of-the-art predictions of peak shock pressures within the tube, highlighting the effect of losses, is shown in Fig. 5. It seemed clear that, if the "no loss" case prevailed, pressures in excess of 40,000 psi at the plugs would render the trench concept infeasible (accepting the premise of an on-line surface burst attack). At the other extreme, the combined effect of all loss mechanisms suggested that this near worst case attack scenario was no more severe than an off-line attack at the 600 psi hardness level, and well within the capability of plug design.

In view of the these extremes, and the uncertainties associated with the theoretical basis for the predictions, a major experimental program was undertaken in early 1977 (see Table 1). The high enthalpy flows required to study the role of ablation (of crucial importance as seen in Fig. 5) could be obtained only from a nuclear source. Accordingly, an underground nuclear test (HYBLA GOLD) was conducted to obtain ablation data on concrete pipes, 15 cm to 90 cm diameter; data on wall friction, tube expansion, and the influence of ribs also were obtained. Description and results of this fascinating test must be obtained elsewhere /9/. Suffice it to say that a wealth of data was obtained which, in conjunction with follow-on laboratory experimentation and considerable theoretical work, led to an acceptably complete understanding of the role of ablation in shock attenuation, the upshot of which is mentioned later.

The major modeling uncertainty associated with venting had to do with early-time expansion and cracking of the overburden, and formation of flow paths to the surface. Sufficiently rapid venting immediately upstream of the blast plug (where reflected pressures increase some seven-fold) would limit the impulse delivered to the plug and suggest an energy absorbing plug design. Because of the need to maintain a free surface, venting experiments were restricted to lower pressure regimes.

Shock tube experiments employing fiber-reinforced concrete models at 1/26-size (6 in inside diameter) were performed to study tube expansion and venting and plug/tube interactions /10, 11/. The models had simulated breakout joints and were buried to scaled depth in representative soils. In-tube pressures of between 400 psi and 3600 psi were generated with an explosively driven shock tube by reflecting the shock from a rigid wall at the end of the test section. A Lucite window was used for the reflecting wall so that the tube and soil response could be photographed from the end by a high-speed movie camera; the soil surface was photographed from the side as well. Pressures were measured within the test section on the reflecting wall and, for the plug tests, behind the plug assembly.

The experimental setup for the expansion and venting tests is shown in Fig. 6. A representative suite of data for one of the tests (700 psi reflected pressure) is presented in Fig. 7. The high-speed movies show that cracks form in the tube almost immediately after shock arrival. The tube then expands symmetrically until a rarefaction wave returns from the free soil surface, whereupon the roof moves off at a greater speed than the lower portion. Typically, venting to the atmosphere begins at a roof crack near the crown when the roof has moved about to the level of the original soil surface.

Once venting starts, the trench "unzips" along its length at roughly the speed of the reflected shock. Over the range of parameters investigated, the roof motion depended on the pressure levels and densities of the soil and tube material, but not on their strengths. Soil strength did affect expansion of the lower tube sections. Roof cracking and vent initiation were influenced by the strength and geometry of the tube; at higher pressures, venting occurred sooner and at correspondingly lesser roof displacement. Venting, even at late times, occurs only directly above the crown.

Candidate M-X blast plug designs combined the concepts of an upstream "leaky plug" which allows some blow-by and a downstream "solid plug" to completely seal off the trench and provide a safe section for the missile/TEL. Three plug/tube interaction tests were performed using smooth and ribbed tube sections; short and long solid plug models and a simplified leaky plug model were used. The experimental setup was the same as in the venting tests, except for a longer shock tube. Additional measurements included pressures behind the plug and reaction forces on the plugs.

The leaky plug model is shown in Fig. 8 and was intended to represent the first of a two-stage leaky/solid plug design. Representative data for a nominal 600 psi incident loading (3600 psi plug face loading) are shown in Fig. 9. A post-test photo is shown in Fig. 10. The results indicated that longitudinal cracking of the tube can defeat the plug function. In both the short solid and leaky plug tests, longitudinal cracks propagated beyond the plug face, allowing the surrounding tube to expand and providing a substantial flow path for the high pressure upstream gas to blow by the plug. However, the longer solid plug performed more successfully, suggesting the feasibility of the two-stage concept. Indeed, by the conclusion of the trench development program, the Air Force had demonstrated two successful full-size blast plugs at the 600 psi design level.

The cooperative effort between theory and experiment led to substantial revision in the computer-based prediction methods and the development of "second generation" codes. These were utilized in an extensive series of parametric analyses dealing with airblast propagation uncertainties /8/. Ablation was determined to be the dominating attenuation effect for near-miss surface bursts (within about 10 m for 1 MT), resulting in pressures at the plug less than those on the surface. Expansion and venting, on the other hand, was found to contribute very little to shock attenuation, contrary to earlier expectations. For off-line attacks where tube collapse is driven by the fireball, surface airblast and ground shock, ablation effects were insignificant and the trench concept appeared entirely feasible.

4. SUMMARY

The design of candidate M-X protective shelters made extensive use of engineering data developed from tests on physical models. This paper has described the effort associated with structural hardening of the three principal M-X shelter concepts: Horizontal Shelter, Vertical Shelter, and Shallow Buried Trench. Primary emphasis was on the trench concept in which a highly coordinated program of theory and experiment provided the data base for (1) characterization of the airblast loading within the trench structure (i.e., shallow buried tube), (2) feasibility determination of blast plug concepts, and (3) developing a minimum cost design for the hardened shallow buried tube.

The experimental activities supporting this effort included laboratory and field shock tube testing, high explosive field testing, and an underground nuclear test. Most innovative, from a structural engineering perspective, was the modeling of (1) coupled airblast and ground shock loading and damage-level response of shallow buried fiber-reinforced concrete tubes, (2) expansion and venting of the tube under internal airblast loading, and (3) coupled flow-structural response of the plug/tube system.

APPENDIX I. - REFERENCES

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APPENDIX II. - TABLES AND FIGURES

TABLE 1. SHALLOW BURIED TRENCH TEST OBJECTIVE MATRIX

		Concept								Validation							
Test Article		Spur	Ring	Tube						Tube/Plug					Plug	Tube Sys.	
Scale		1/26	1/2	1/9	1/26	1/9	1/6	1/4	Full	1/13	1/6	1/26	1/13	1/4	1/4	1/2	3/4
Objective / Test Env.		D	S	S	D	D	D	D	—	S	S	D	D	D	D	D	D
Environment	Airblast																
	--External																
	--Internal	●			●			●				●		●		●	●
	Ground Shock																
Test Methods	Instrumentation							●								●	●
	Simulation																
	--External							●								●	●
	--Internal							●						●		●	●
	--Scaling													●		●	●
Hardness Design Data	Analytical Model Dev. & Eval.		●											●	●	●	●
	Design Concept Screening		●	●		●	●	●		●	●		●			●	●
	Structure/Media Interaction			●		●	●	●						●		●	●
	Structure Element Interaction									●	●		●	●	●	●	●
	Fragility/Ductility Determination		●			●	●	●		●	●		●				
	Scaling					●		●		●	●		●	●		●	●
	Constructability								●								
	Breakout															●	
	Static/Dynamic Correlation			●		●				●			●				

S-Static D-Dynamic

TABLE 2. HORIZONTAL SHELTER TEST OBJECTIVE MATRIX

	Test Article	Concept Validation				Full Scale Engineering Development												
		Closure		Shelter		Cylinder		Closure		B.O. Joints		Sal Ports		Back Fill		Shelter		
	Scale	1/6		1/6	1/2	1/6		1/6		1/6		1/6		1/6		1/100	1/21	1/5
	Objective / Test Env.	S	D	D	D	S	D	S	D	S	D	S	D	S	D	D	D	D
Environment	Airblast																	
	-Single Burst			●								Tested in Conjunction with Static & Dynamic Cylinder Tests					●	●
	-HOB															●		
	Groundshock			●														●
	Multiburst															●		
Test Methods	Instrumentation			●														●
	Simulation																	
	-Scaling			●													●	●
	-Fidelity			●	●												●	●
Hardness Design Data	Analytical Model Dev. & Eval.			●			●		●									●
	Design Concept Screening	●	●			●	●	●	●	●								
	Structure/Media Interaction			●		●	●											●
	Structure Element Interaction			●	●	●	●											●
	Fragility/Ductility Determination	●	●			●	●	●	●	●								
	Scaling			●	●													

S-Static D-Dynamic

TABLE 3. VERTICAL SHELTER TEST OBJECTIVE MATRIX

		Concept Validation							
Test Article		Closure		Cylinder		Shelter			
Scale		1/6		1/6		1/30	1/6	1/3	Full
Objective	Test Env.	—	D	S	D	D	D	D	—
Environment	Airblast	Tested in Conjunction with Shelter Tests and in Hard Rock Silo Program							
	-Single Burst								
	-HOB								
	Groundshock							●	
	Multiburst								
Test Methods	Instrumentation				●		●	●	
	Simulation								
	-Scaling							●	
	-Fidelity								
Hardness Design Data	Analytical Model Dev. & Eval.				●		●	●	
	Design Concept Screening			●	●	●	●	●	
	Structure/Media Interaction				●	●	●	●	
	Structure Element Interaction					●	●	●	
	Fragility/Ductility Determination			●	●				
	Scaling					●	●	●	
	Constructability								●

S-Static D-Dynamic

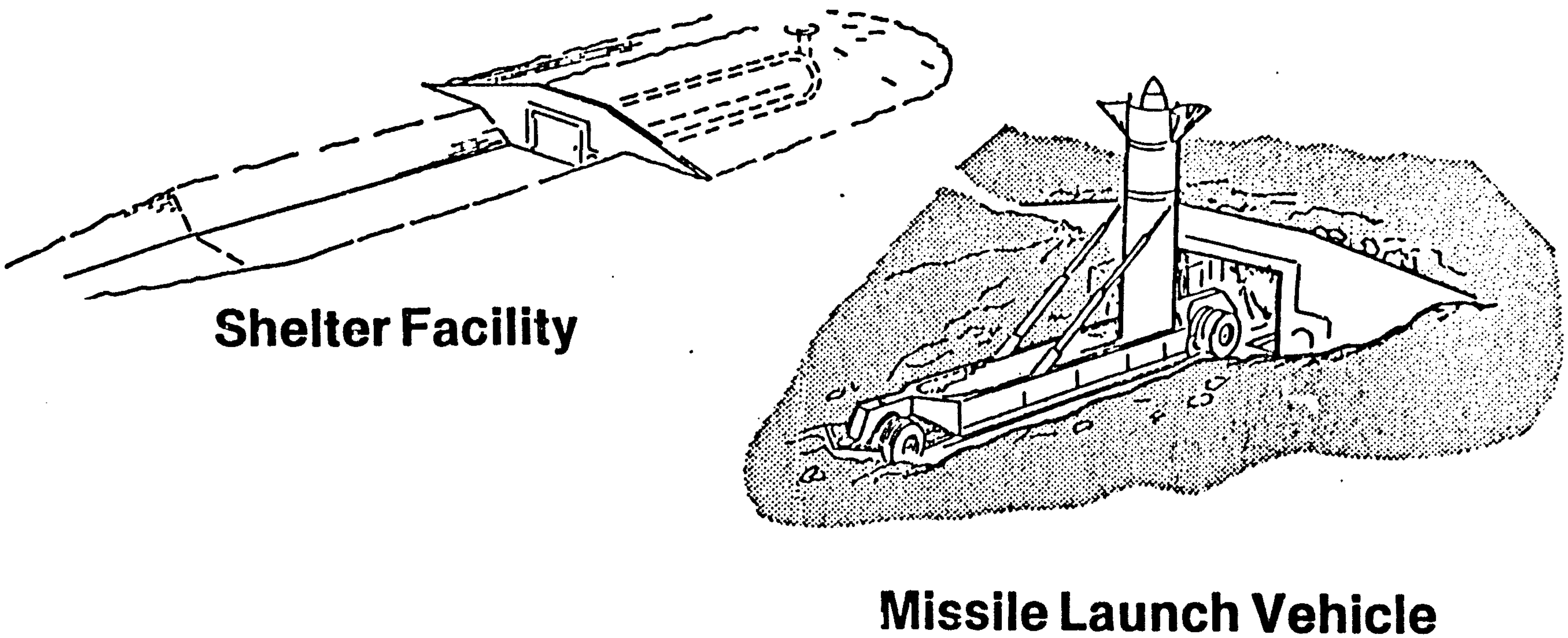
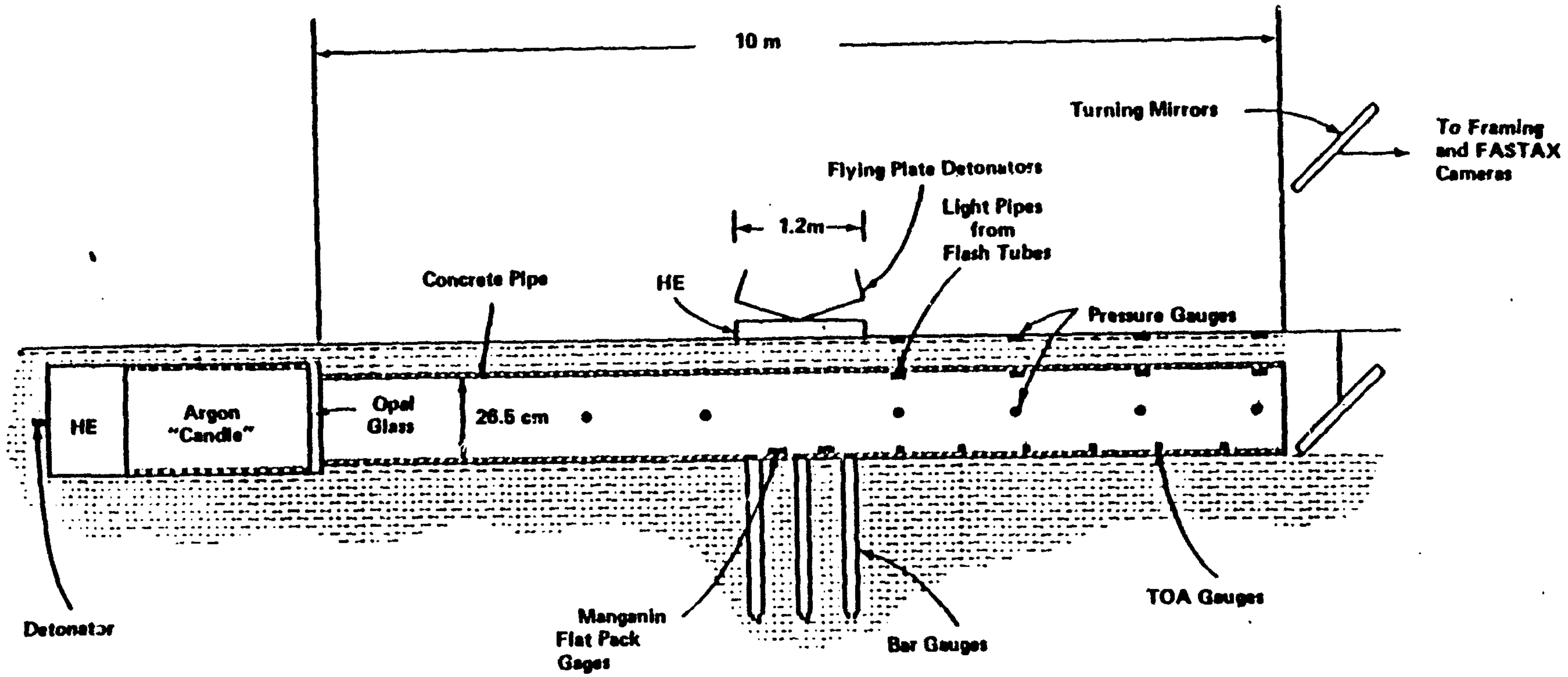


Fig. 1. MX horizontal protective shelter concept



Note: Horizontal and vertical scales are different.

Fig. 2. Experimental set-up for ground shock-induced collapse

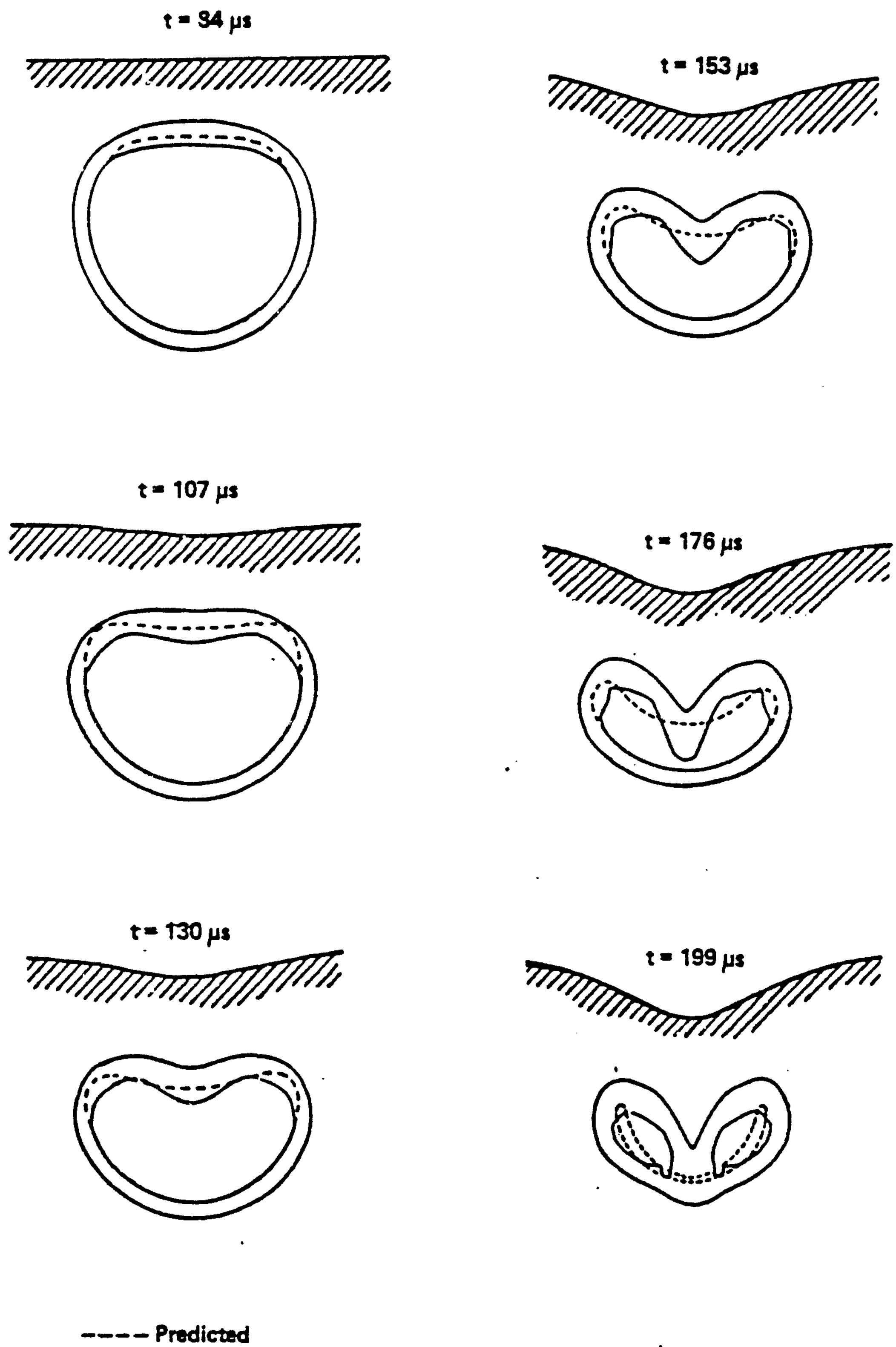


Fig. 3. Tube crush-up: Comparison of measurements and predictions

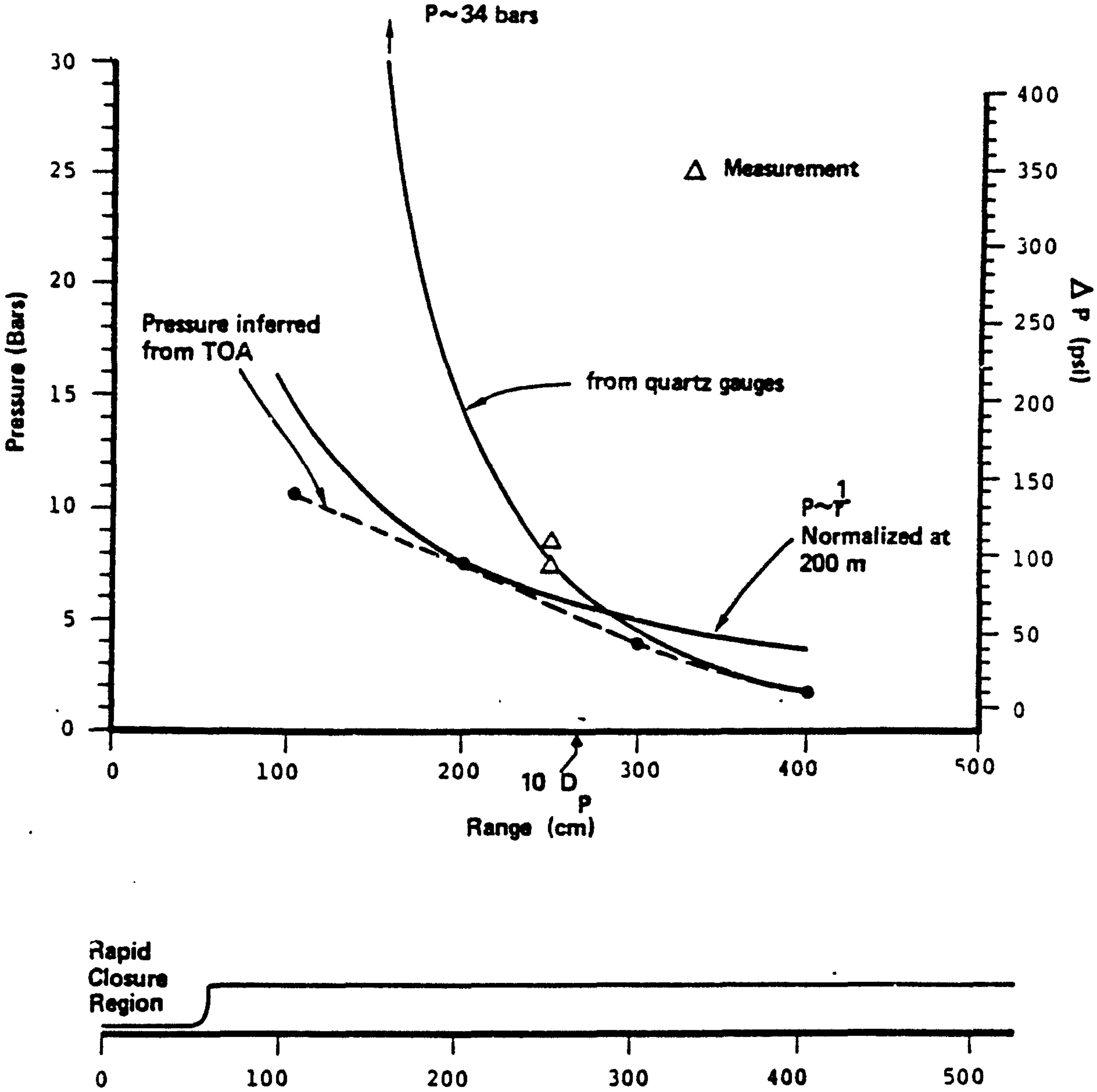


Fig. 4. Airblast pressures generated by tube crush-up

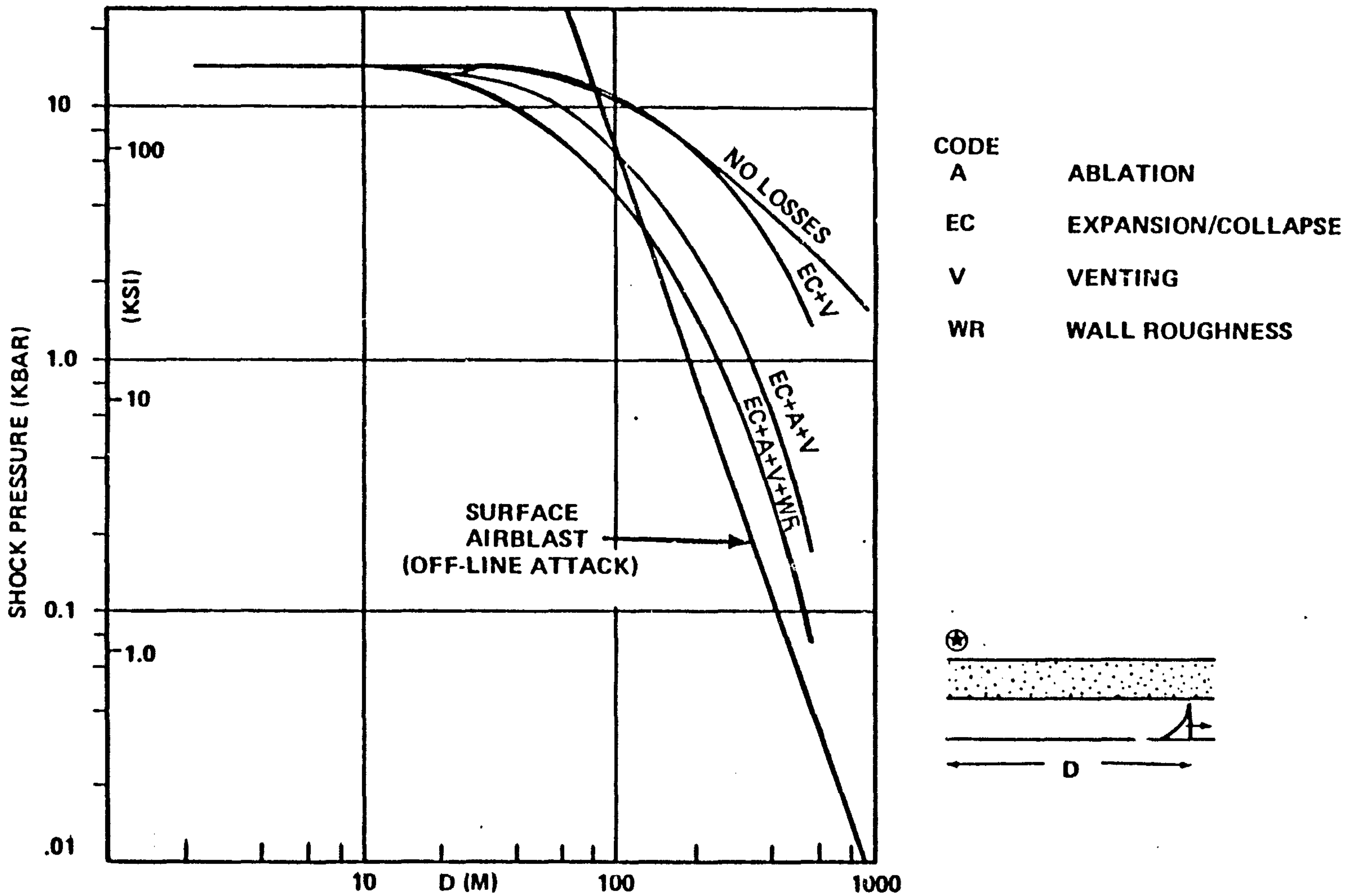


Fig. 5. Estimated in-tube airblast from a 1 MT on-line surface burst

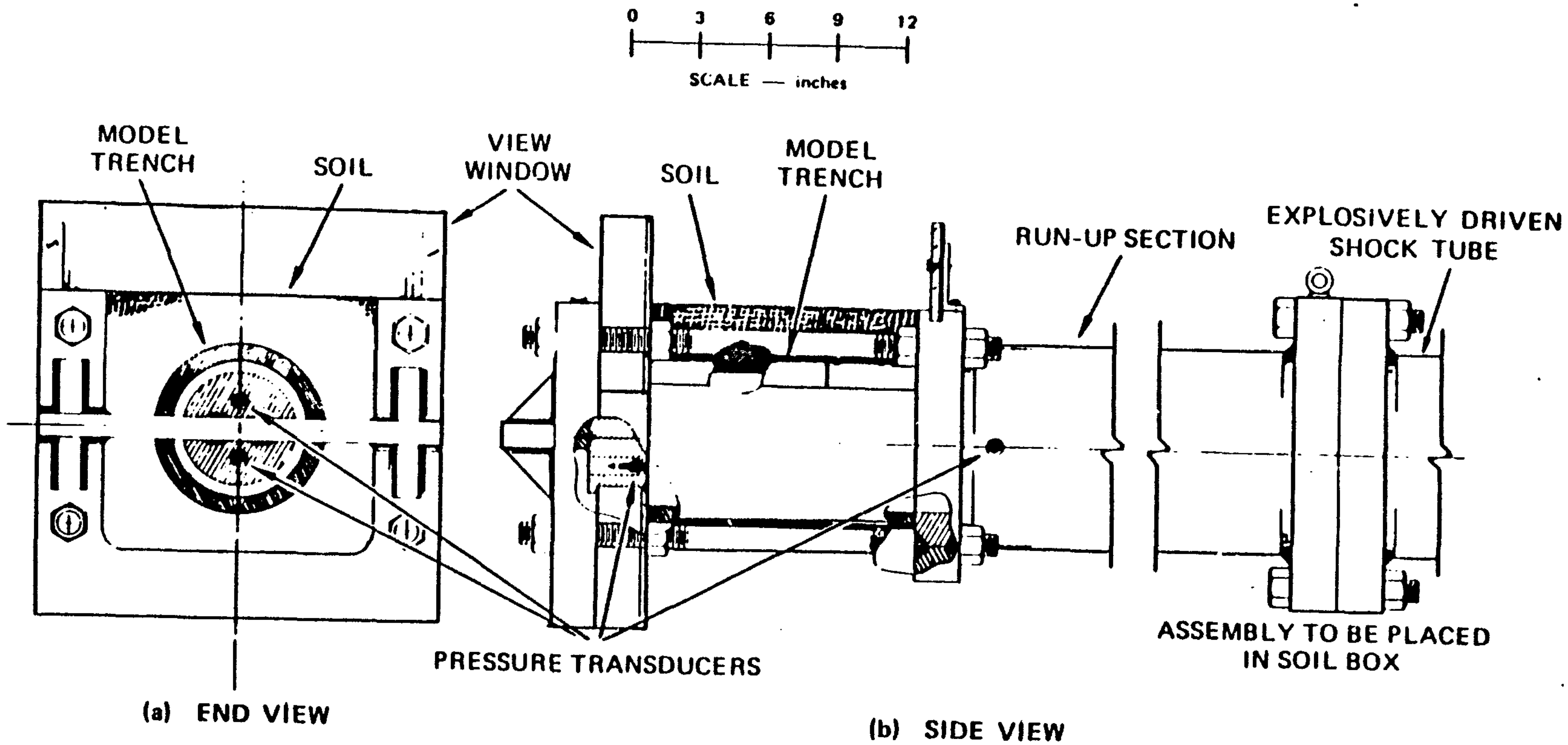


Fig. 6. Experimental set-up for tube expansion and venting

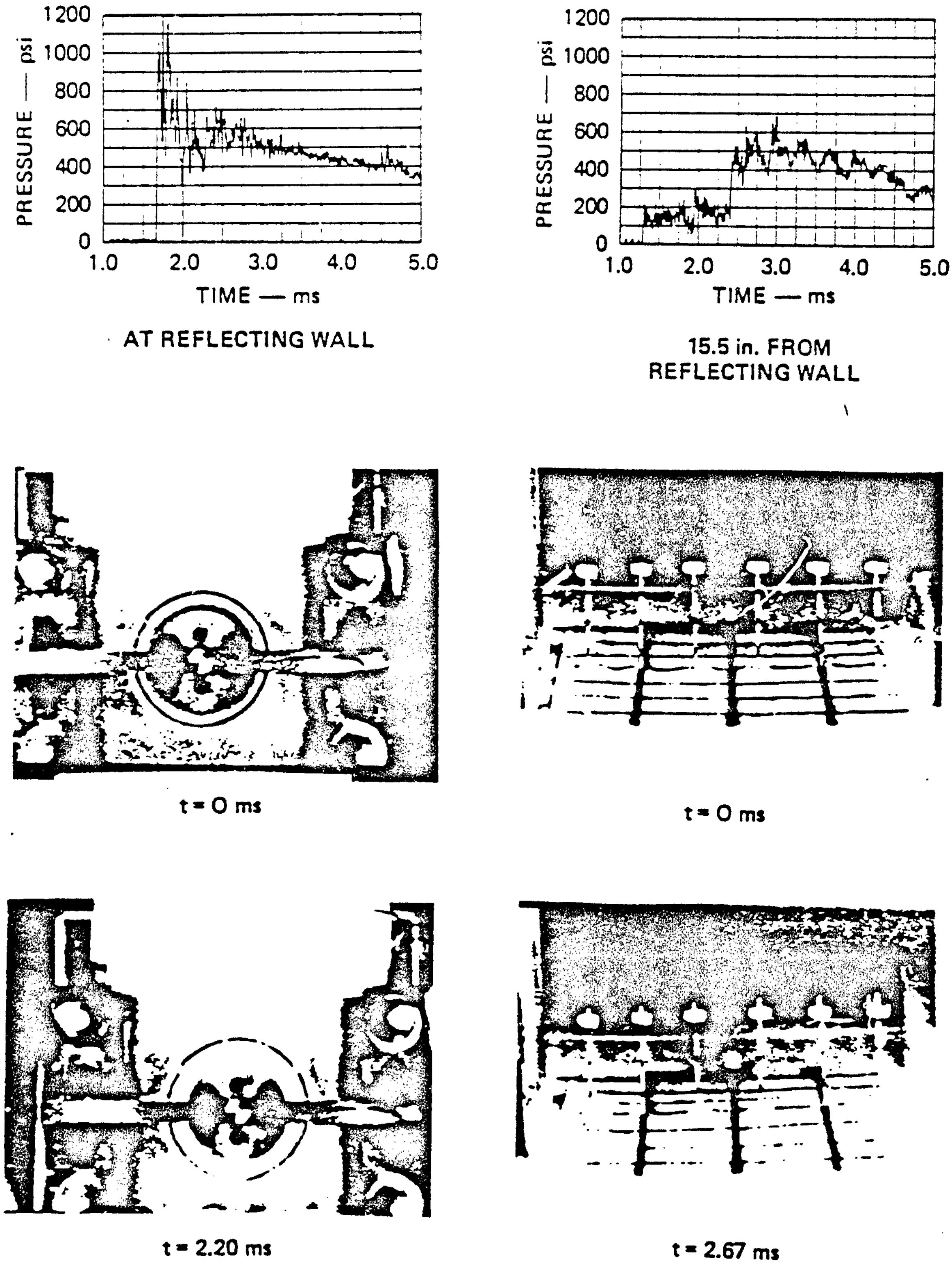
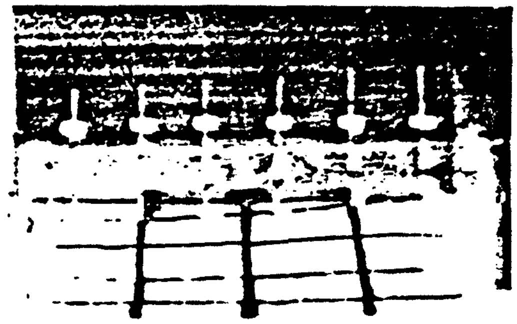


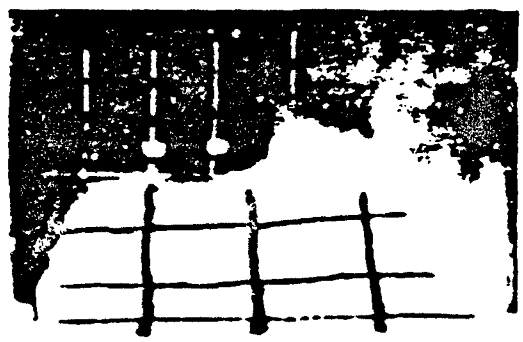
Fig. 7. Selected results from tube expansion and venting tests

t = 3.71 ms

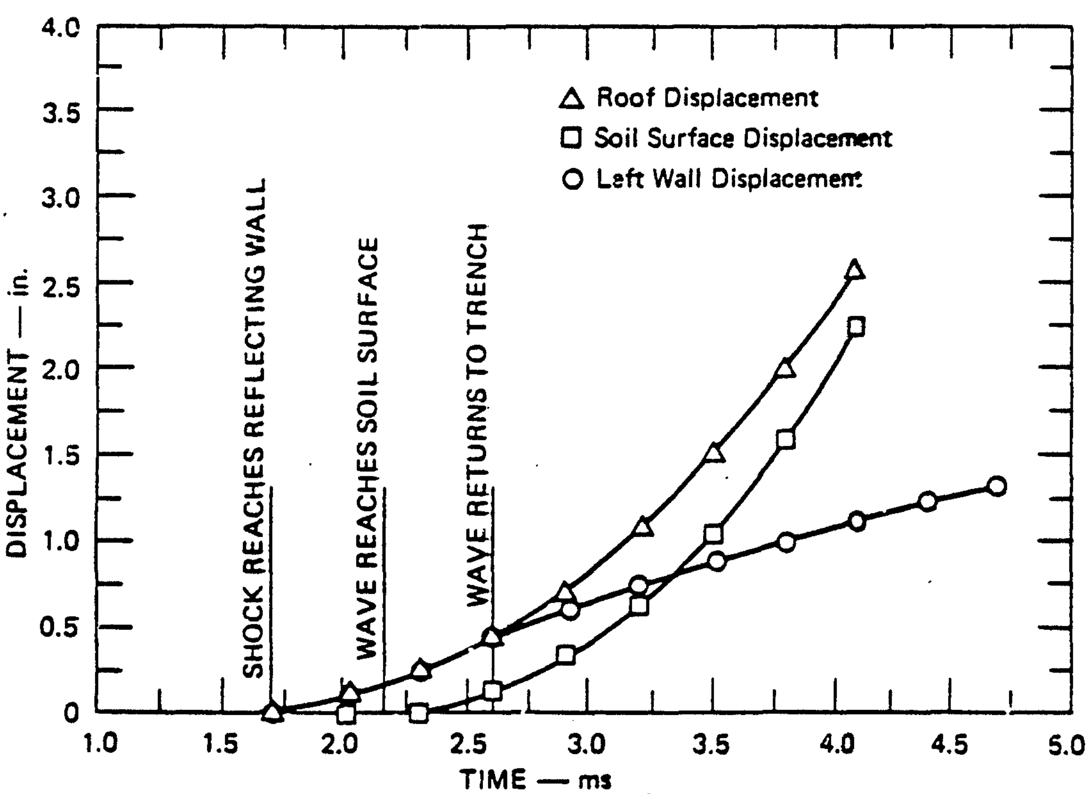


t = 3.43 ms

t = 4.21 ms

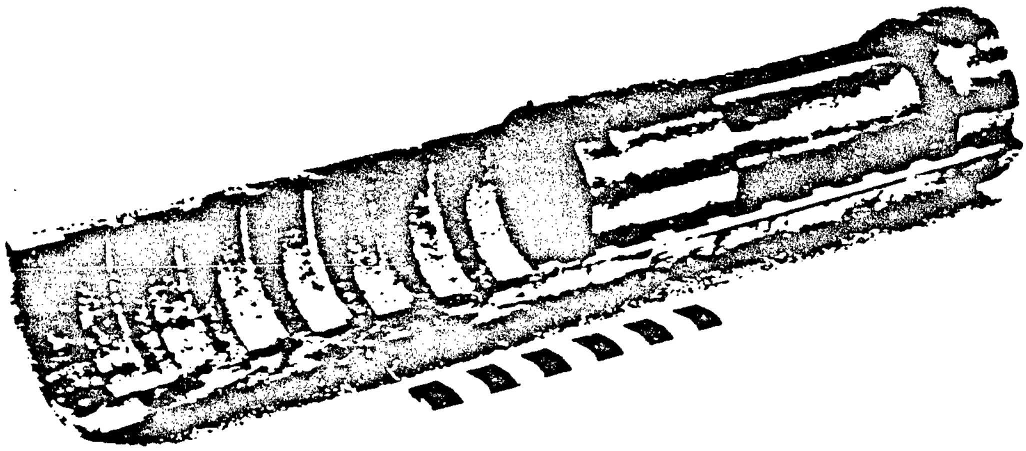


t = 4.47 ms



SYMMETRIC TRENCH EXPANSION PHASE (Test 17)

Fig. 7. (continued)



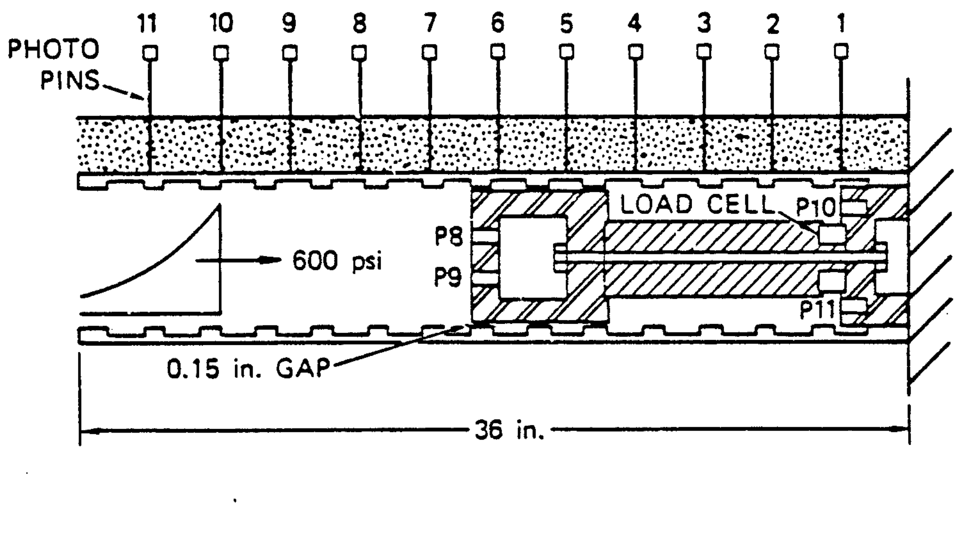


Fig. 8. Leaky plug model for plug/tube interaction tests

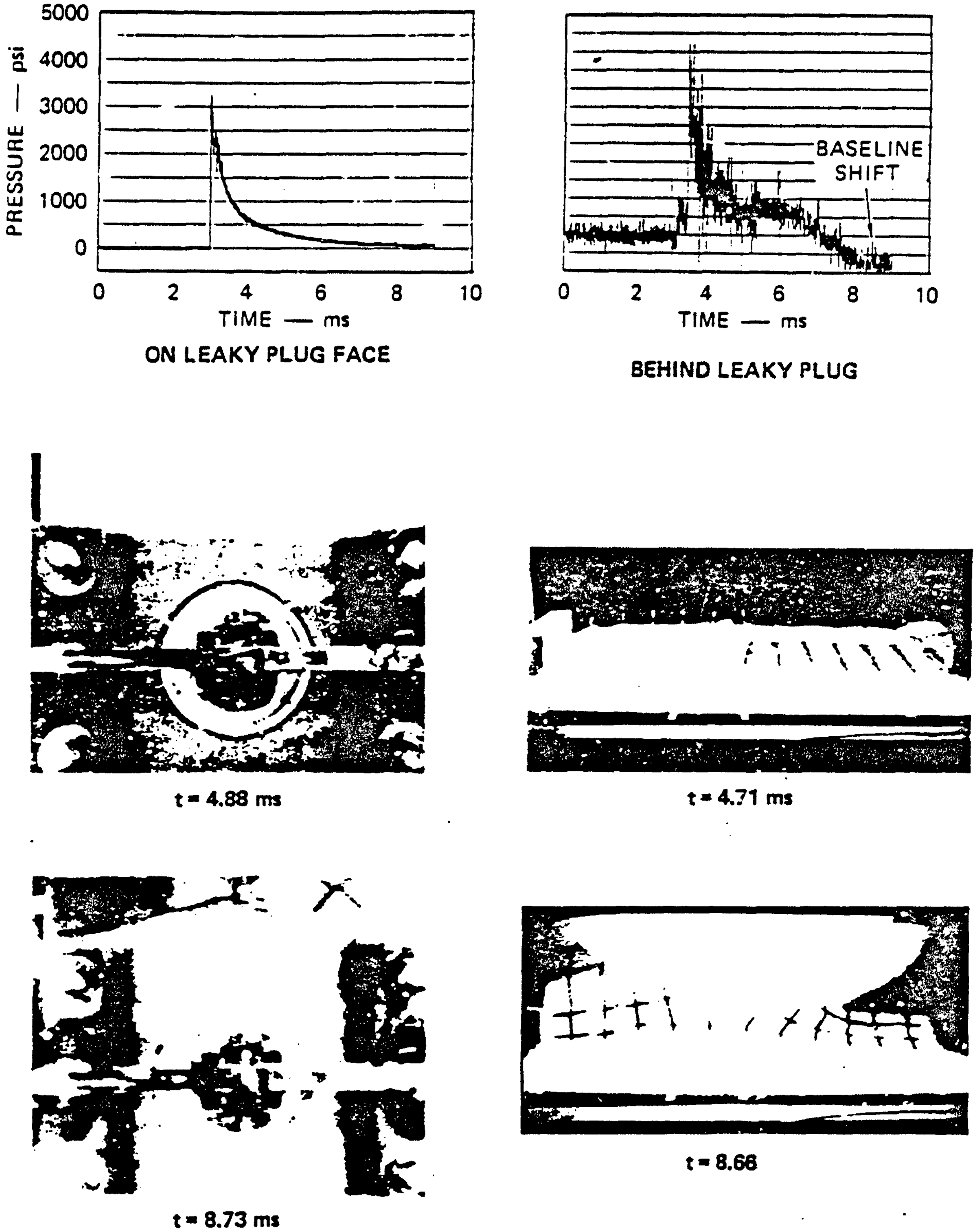


Fig. 9. Selected results from leaky plug/tube interaction test

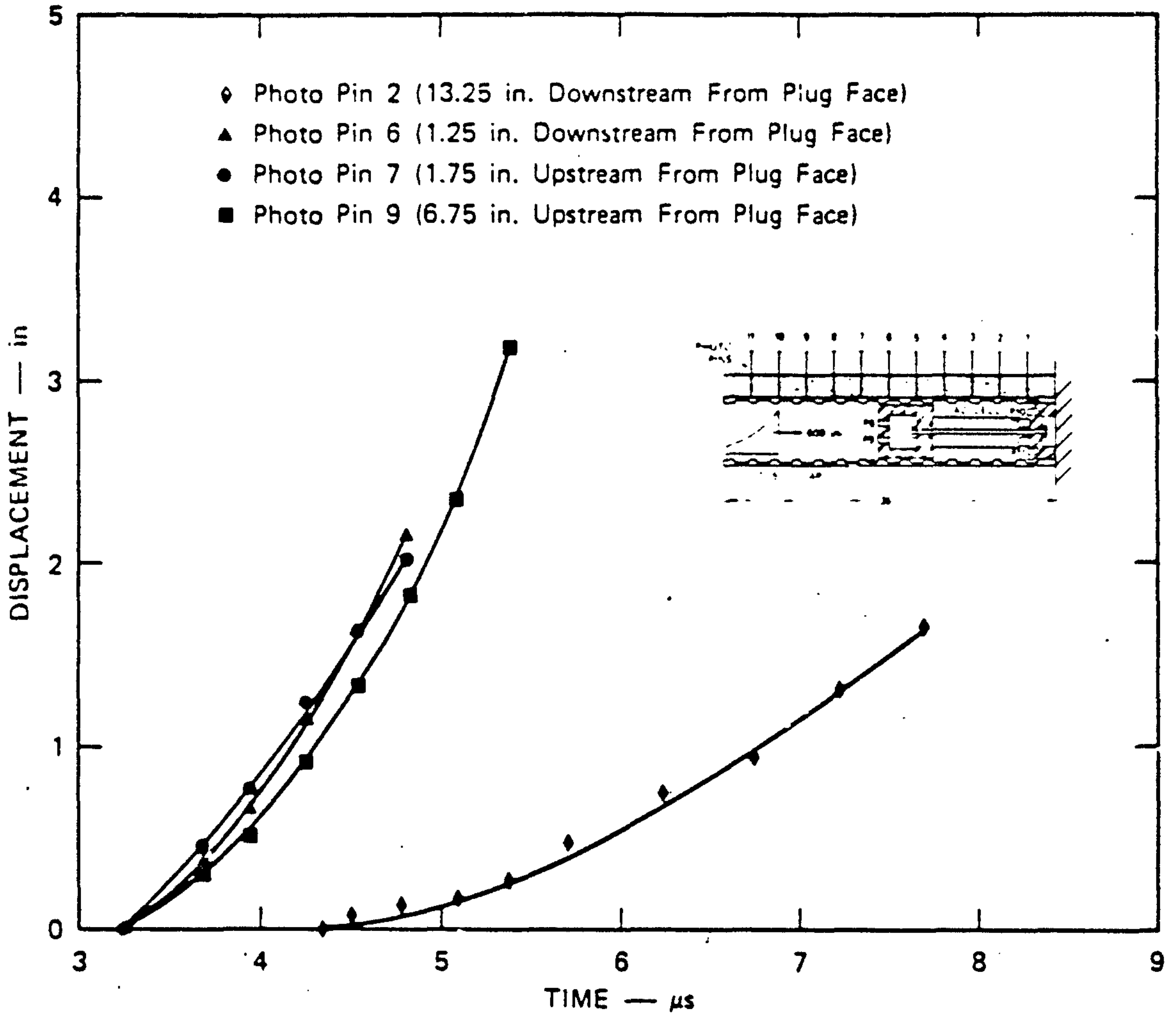


Fig. 9. (continued)

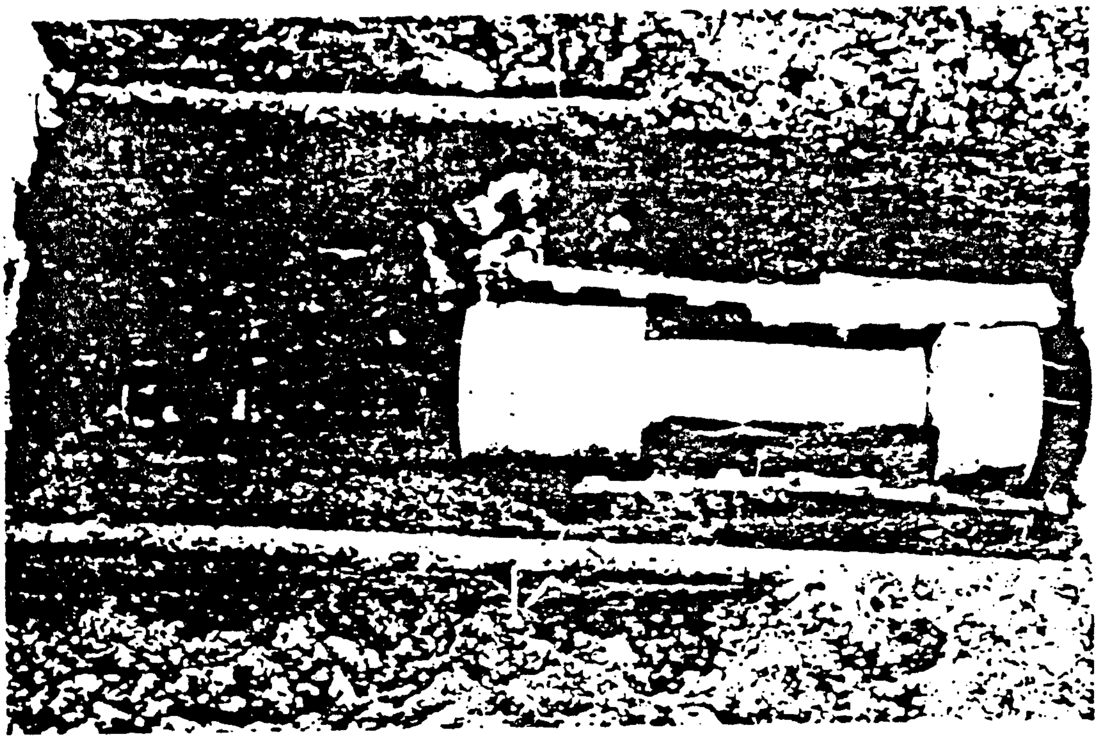


Fig. 10. Post-test condition of leaky plug/tube (after soil removal)